Space and Flights Radiation Protection

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Abstract. This keynote lecture provides basic information on different aspects of radiation protection during space missions and related to the aircraft transport. Under the quiet solar conditions, the level of exposure onboard aircraft is up to two orders of magnitude higher than natural radiation environment background, whereas onboard spacecraft exposure is still several times higher. Intense, fortunately very rare, solar eruptions can increase these levels still many times. It is evident that the radiation protection considerations related to onboard aircraft and/or spacecraft exposure have to be designed differently when compared to the Earth surface. First, the basic characteristics of radiation fields in space, onboard spacecraft and aircraft are briefly outlined. Afterwards, main principles of radiation protection approaches to these types of exposures and theirs management are presented. Methods and procedures available to determine dosimetric and microdosimetric characteristics of near Earth radiation fields are also presented. Some results of onboard measurements are shown, mostly authors own experience is considered in this respect. Results of long-term individual monitoring of aircraft crew in Czech Republic are also presented analysed and discussed.

KEYWORDS: cosmic radiation; solar proton events, space radiation fields; dosimetry and microdosimetry onboard space- and aircraft; space and flights radiation protection

1. Introduction

One of the important components of the exposure of humans to natural ionizing radiation is the radiation originated in space. During several last decades technological and other developments of human society have brought an important increase of the exposure to this ionizing radiation. This increase is related first to the air transport, in last tens years also to space exploration. The level of exposure to these sources of radiation increases with the altitude above the Earth's surface. Radiation fields in near-Earth area change also qualitatively; they differ from the most of radiation fields on Earth. This lecture gives basic characteristics of these radiations, discusses the possibilities of their dosimetry and microdosimetry, and, also, outlines the basic principles of space and flights radiation protection.

2. Space radiation sources, radiation fields near-Earth area.

2.1 Space radiation sources [1-7].

The Earth is continuously bombarded with high-energy ionising radiation from outer space. The cosmic radiation field in the Earth's atmosphere has two different origins: energetic particles from the galaxy and the sun. Besides, there are two other possible sources of radiation exposure: the particles trapped in Earth's magnetic field, and those scattered from the atmosphere.

Galactic cosmic radiation (GCR)) is composed mostly of protons (~85 %) and helium ions (~12 %), the rest includes nuclei of all known elements and some electrons. Their energy extends up to about 10^{20} eV. Typical energy spectra of GCR are presented in Fig.1. One can see that the most probable proton energy is about 1 GeV, a little lower during solar minimum. For heavier ions, the most probable energy declines in comparison to protons. The GCR as well as other space radiation is modulated by Earth magnetic field, expressed through so-called cut-off rigidity, which is the most important close to the equator, practically missing close to Earth's magnetic poles. Both solar activity level as well as the cut-off rigidity diminishes particularly the contribution of lower energy particles.
Typical annual exposure levels due to GCR are, as a function of water shield thickness, presented in terms of annual D and H values in Fig.2. One presents there also the QF values.

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Figure 1: GCR particles energy spectra

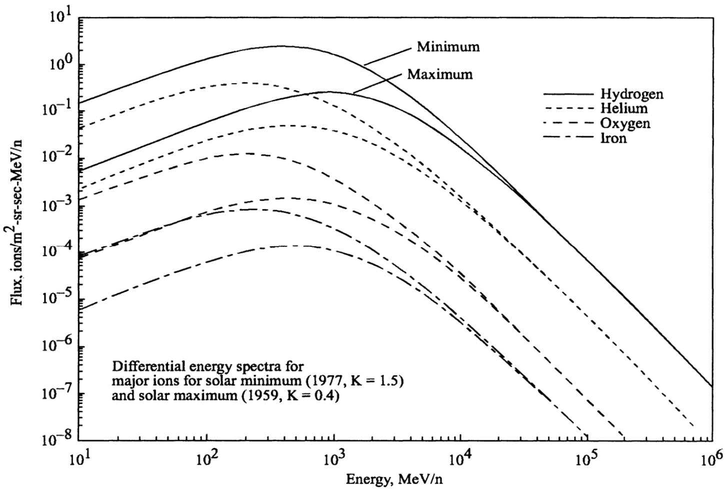
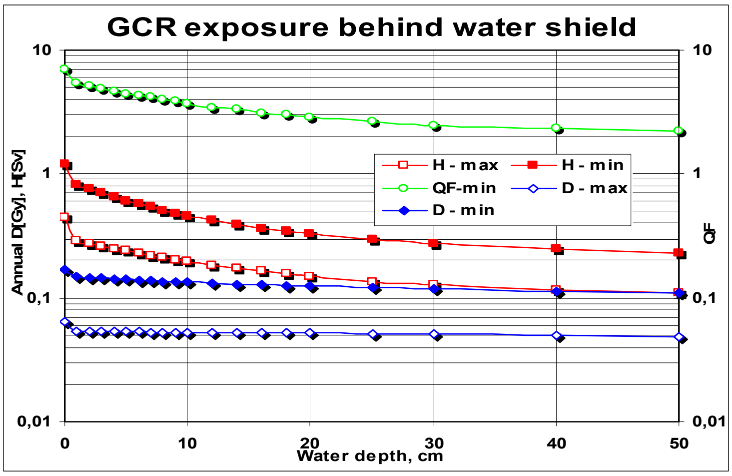


Figure 2: Annual values of D and/or H as a function of water shield and solar activity



One can see there that:

- Annual value of dose equivalent in open space is about 1 Sv at the solar minimum, 0.4 Sv at the solar maximum; corresponding dose annual values are about 0.17, 0.06 Gy, resp.
- At shield thicknesses of 20 – 30 g.cm^{-2}, H values decrease about 3 times, D values decline slower.
- Radiation quality changes with the depth. Without shield, with important contribution of heavier ions (group of Fe), total QF is about 5 to 6. At 20–30 g.cm^{-2} it decreases to about 2.5.

Solar energetic charged particles can contribute to space and flight exposure through occasional solar particle events (SPE's). During them, large number of mainly high-energy protons is produced. Only a small fraction of the SPEs can be observed as ground level events (GLE's), because the proton energies exceed l GeV only rarely. The duration time of a SPE may extend from hours to several days. The prediction of events giving significant increases in dose rates is not currently possible. There exist some estimations of dose equivalent for human in space during some extreme SPE. Results of one of them [7] are presented in the Table 1. One can see there that these values could be extremely high. For that reason, areas with increased shield thicknesses are usually build onboard of space vehicles.

Radiation belts consist of protons and electrons trapped in various altitudes and inclinations. The energies of electrons do not exceed a few MeV, while the proton energies reach a several hundred MeV,. However, both electrons and protons can be effectively shielded. One distinguishes two

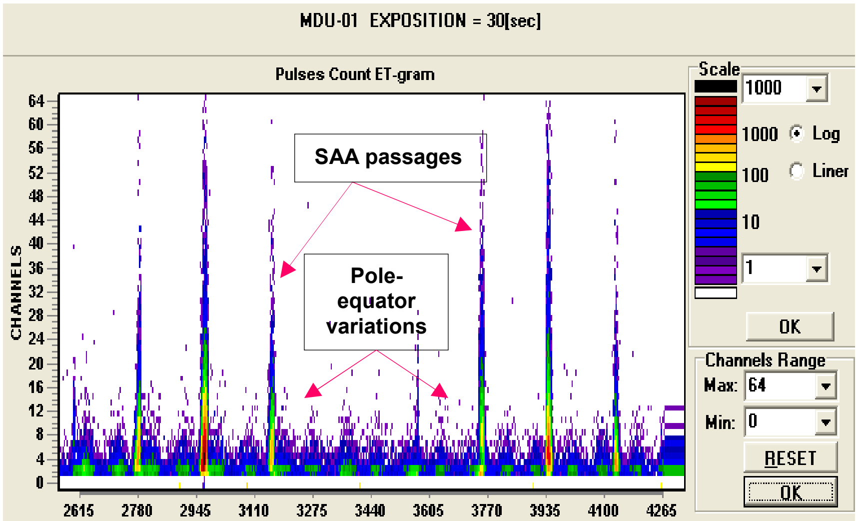
radiation belts: internal, with the central part at about 3000 km from the Earth's surface, and external, centred at about 20000 km. Spacecrafts with inclinations about 50^{o} cross the internal radiation belt in the area of South Atlantic Anomaly (SAA), east from the Brazilian coast of Atlantic ocean. The record of the measurements by means of a device onboard of a satellite crossing SAA is shown on the Fig. 3.

Table 1: Estimated dose equivalent in humans during some extreme SPE's.

Shield thickness, g.cm^{-2}	Solar event[1)]	H, Sv, in		
		Skin	Ocular lens	Blood forming organs
2	08/72	11.3	9.1	1.24
2	Worst case [2)]	15.5	13.0	4.40
20	08/72	0.18	0.17	0.07
20	Worst case [2)]	3.02	3.04	2.62

[*)] worst scenario: GLE 23/05/56 with 10times higher flux than that of GLE of 29/09/89

Figure 3: Record of the dose measurements onboard a satellite by means of Liulin device



It is evident, that dose rates during SAA passages are by order of magnitude higher. As a result, roughly the half of all exposure onboard International Space Station (ISS) (inclination 51.6^{o}), is due to the SAA passages. To resume, the exposure to space radiation can differ following the situations, missions, the appearance of a SPE etc. Recently, typical doses at some situations have been calculated, they are given in Table 2 [3,7].

Table 2: Doses in blood forming organs from GCR (1977 minimum) and /or SPE; shield 10 g.cm^{-2}

Radiation; unit	Area	Effective dose
GCR Sv per year	Open space Moon Mars	0.59 0.29 0.12
GCR; Sv	Mission to Moon (190 days) Mission to Mars (947 days)	0.18 0.92
SPE[*)], Sv	Open space Lunar surface Mars surface	1.3 0.60 0.25

[*)] worst scenario: GLE 23/05/56 with 10times higher flux than that of GLE of 29/09/89

2.2 Radiation fields and exposure levels onboard flying crafts

2.2.1 Spacecraft boards [5-9]

The GCR interacts with the atmosphere producing secondary radiation, which together with the primary incident particles give rise to radiation exposure. The radiation field onboard spacecraft is formed through the interactions of both primary space and secondary radiation in the spacecraft construction materials, equipments installed onboard, other materials, astronauts' bodies included. Usually, the radiation field onboard spacecraft (typical shield thicknesses of space vehicles are 20 – 50 $g.cm^{-2}$) is divided to two components:

- The component with low, (below 10 keV/µm in tissue) linear energy transfer (LET), consisting of high-energy protons, electrons, photons, and mesons, and
- The component with high LET, consisting of heavier GCR ions and their high energy secondaries (fragments, products of nuclear interactions), and neutrons with energies ~0.1 up to 100's MeV.

Complex composition of space radiation and dynamic nature of energy and angular spectra in habitable compartments of the stations do not permit to obtain sufficiently accurate data on radiation conditions only by calculations, real in-flight radiation dose measurements are necessary.

As mentioned above, doses onboard spacecraft depend also on:

- solar cycle phase; helio- and geophysical parameters
- the spacecraft orbit parameters such as orbit inclination, altitude, and so on; and
- spacecraft shielding.

The results of radiation monitoring during long-term space missions onboard the MIR and ISS demonstrate [8] that annual crewmember dose equivalent can vary from 0.1 to 0.3 Sv, its dose rate being from 0.3 to 0.8 mSv/day. In case of solar particle events, especially during the flights outside the Earth magnetosphere, the above mentioned doses can be substantially higher.

2.2.2 Aircraft board [10-13]

Cosmic radiation at the aircraft altitudes is composed mostly of secondary particles created during the interaction of primary cosmic rays in the Earth's atmosphere. At the altitudes of subsonic air transport (11-14 km), the radiation field can be divided into two parts:

- the component with the low linear energy transfer (LET), represented mostly by the electrons, photons and the high energy protons; and
- the component with high LET, represented mostly by neutrons with energy up to hundreds MeV.

These components contribute to the exposure level roughly by one half. Onboard exposure originates mostly from the galactic cosmic radiation. It is therefore predictable, with the exception of very rare giant solar flares. The exposure level decreases when the solar activity increases, with roughly 11-year solar cycle (see Fig.4). Fig. 5 shows the influence of geographic position (cut-off rigidity), Fig. 6 shows the influence of flight altitude, geographic position, and solar activity.

When a giant solar proton event arrives, exposure level onboard aircraft can substantially increase. A recent estimation of this increase for 31 such events since 1942 is given in Fig. 7. One can see there that this contribution could reach about 5 mSv for the largest SPE (February 1956), some recent estimation has given lower values [17].

Figure 4: Opposite trends in solar activity and the counting rate of a neutron cosmic ray monitor

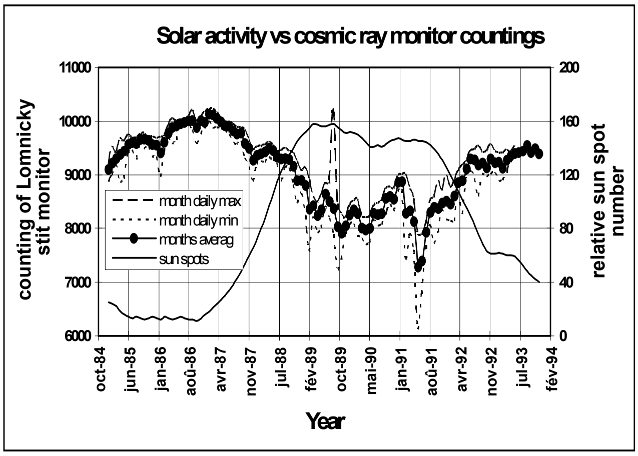


Figure 5: Geographic variations of the dose equivalent rate at the altitude 41000 feet and the heliocentric potential 420 MV (low solar activity) as calculated by means of code CARI [14].

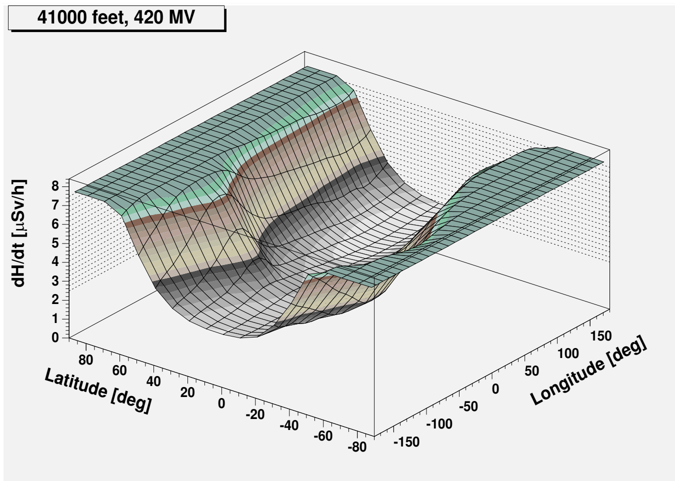


Figure 6: Calculated dH*(10)/dt, for conditions close to solar maximum (Jan.1990) and close to solar minimum (Jan. 1998), at zero-meridian (λ=0°) and geogr. latitude ϕ of 0° (red) resp. 90°(blue) [15].

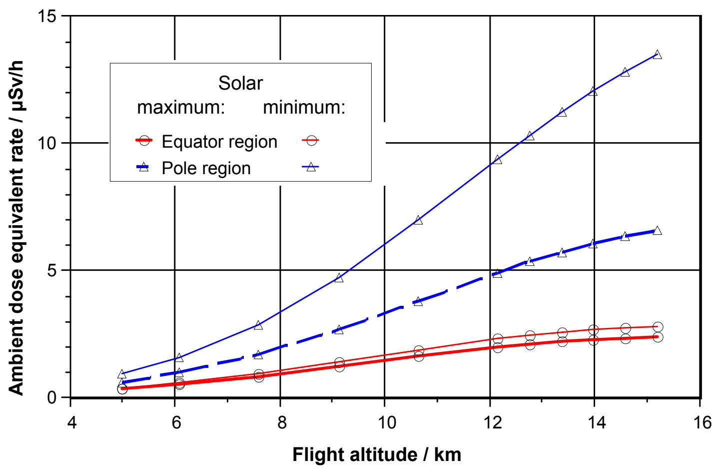
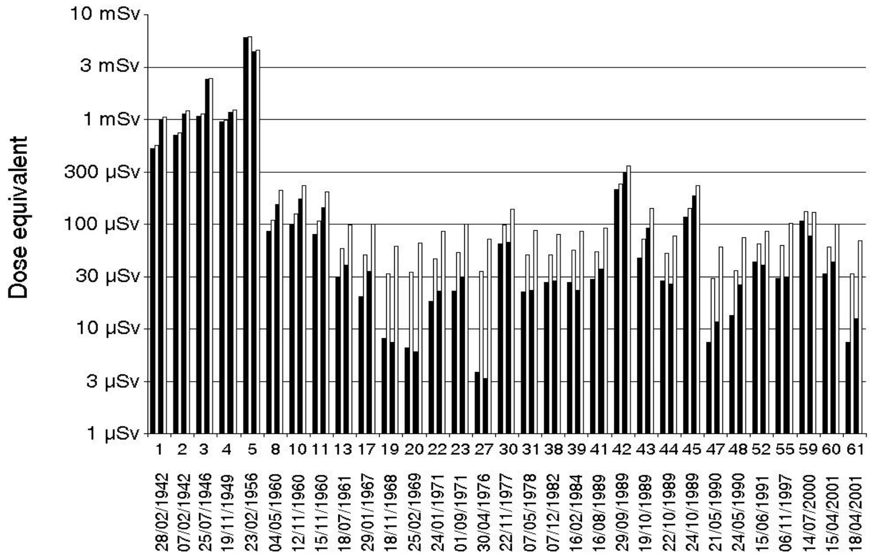


Figure 7: Worst case of calculation for 31 GLEs for flights between Paris - New York (Concorde) (1st and 2nd bar) and Paris - San Francisco (subsonic) (3rd and 4th bar). GLE-black bar, D_{tot} - white bar [16].



3. Radiation protection aspects of space exploration and aircraft transport

3.1. Basic principles

The following statement still represents the position of the International Commission on Radiological Protection on the hazard related to the exposure to ionizing radiation in general:

The primary aim of radiological protection is to provide an appropriate standard of protection for man without unduly limiting the beneficial actions giving rise to radiation exposure. This aim cannot be achieved on the basis of scientific concepts alone. All those concerned with radiological protection have to make value judgements about the relative importance of different kinds of risk and about the balancing of risks and benefits. In this, they are no different from those working in other fields concerned with the control of hazards.'

The current system of radiological protection on Earth, still based on the recommendations formulated in ICRP Publication 60 [24], is very comprehensive. It can be briefly characterised as:

1. Two types of radiation effects are distinguished:
   - Deterministic – characterized by a threshold
   - Stochastic – no dose threshold, probability increases with dose – LNT concept

2. Radiation protection would:
   - exclude the possibility of deterministic effects
   - limit the stochastic effects at the level as low as reasonably achievable.

3. To assure that, three basic principles of radiation protection have to be considered:
   - Justification - final effect of the activity leading to an exposure would be positive
   - Optimization – keeping of the exposure as low as achievable, and
   - Limitation - not exceeding of limits

4. Basic radiation protection quantities and units are [11,19,23,24]:

absorbed dose	$D = (d\varepsilon/dm)$
organ dose	$D_T = (\varepsilon_T/m_T)$
equivalent dose	$H_{T,R} = w_R \,.\, D_{T,R}$, resp. $H_T = \sum R w_R \,.\, D_{T,R}$
effective dose	$E = \sum T w_T \,.\, H_{T,}$

where T denotes organ (tissue), and R denotes the radiation; $w_{T,}$ resp. w_R are tissue, resp. radiation weighted factors.

Principally; the effective dose is not measurable quantity, that's why operational quantities are also introduced. Basic of them is **dose equivalent** H = Q . D , where Q is quality factor.

To characterize the exposure in whole body, the basic quantities are:
ambient dose equivalent H*(d), is used for "free – in air" irradiation geometry, while
personal dose equivalent Hp(d) characterise the personal exposure;
for both types of whole body exposure one takes d = 10 mm

3.2. Dose limits for on Earth occupationally exposed persons

The ***effective dose E*** received during any consecutive 12-month period shall not exceed 20 mSv. Once pregnancy is diagnosed the woman shall no longer be authorized to work regularly in a controlled area and shall be subjected to an effective dose of smaller than 1 mSv during the period of pregnancy.

The dose equivalent limits for the exposure of the ***separate organs*** of the body H_{org} for 12 consecutive months shall not exceed: 500 mSv for hands and forearms, feet and ankles, 300 mSv for skin, and 150 mSv for eyes.

3.3. Dose limits for aircraft crew members

The level of exposure at the air transport altitudes is, as already mentioned, much higher than closer to the Earths' surface. Besides, there are significant differences in exposure characteristics of aircraft crew members and occupational exposures generally [10-12]:

- the fraction of effective dose deposited by high LET radiation is much greater for aircrew, about 50 % as compared to few percents only for others; and,
- there are a little more than one half of females among aircrew members, while they represent only few percents for other occupationally exposed persons.

Both these two factors increase the importance of correct estimation of aircrew exposure.

Considering usual total annual flight times of crew members (≤1000 hours), the same limits are adopted for them as for other on-Earth occupationally exposed persons.

3.4. Dose limits for astronauts

Space and onboard spacecraft exposure levels are still more important; the number of persons involved in this type of activity is incomparably low when compared with aircraft crew members (few hundreds compared to few thousand hundreds). The overall objective to assess and control the radiation exposure of individual astronauts can be broken as follows [6]:

1. keep individual doses below the established limits to avoid deterministic effects;
2. keep accumulated doses over an astronauts career below the limits for stochastic effects; and
3. keep all astronaut doses as low as reasonably achievable, economic and social factors taking into account (ALARA principle).

In the context of near-Earth space activities, one must also consider the mission requirements and radiation conditions in low Earth orbits (LEO), extravehicular activities (EVA) included.
When US approach is taken into account [6], dose limits for astronauts are designed different from those for on-Earth and aircraft occupational workers:

1. Limits for stochastic effects are still expressed in the term **of *effective dose.*** Theirs values are presented in Table 3.

Table 3: Ten year carrer E limits**, in Sv,** based on three percent*) excess lifetime risk of fatal cancer

Age at the 1st exposure, years	Female	Male
25	0.4	0.7
35	0.6	1.0
45	0.9	1.5
55	1.7	3.0

*) to add 0.6 % of heritable effects, and 0.6 % of nonfatal cancer

2. Limits for deterministic effects are expressed in terms of Gray-equivalent, $\mathbf{G_T}$, where $\mathbf{G_T}$ is the mean absorbed dose in an organ, $\mathbf{D_T}$, multiplied by a recommended value of the relative biological efficiency for the radiation **i; $\mathbf{R_i}$.**

The values of $\mathbf{R_i}$ to be used to convert for deterministic effects $\mathbf{D_T}$ to $\mathbf{G_T}$ are given in Table 4.,also for them the limits depends on the organ and exposure length and type – see Table 5.

Table 4: $\mathbf{R_i}$ for converting $\mathbf{D_T}$ to $\mathbf{G_T}$ for deterministic effects

Particle type	R_i (range of values)
1 to 5 MeV neutrons	6.0 (4-8)
5 to 50 MeV neutrons	3.5 (2-5)
Heavy ions (e.g., helium, carbon, neon, ardon)	2.5 (1-4)
Protons > 2 MeV	1.5 (--)

Table 5: Recommended $\mathbf{G_T}$ limits , in Gy-Eq, for deterministic effects (all ages)

	Bone marrow	Lens of the Eye	Skin
career	-*)	4.0	6.0
1 y	0.50	2.0	3.0
30 d	0.25	1.0	1.5

*) as for stochastic effects

It should be mentioned that the system of limitations is in other countries a little different, a review of them can be found in [3,7]

Some remarks to space and flights radiation protection management

***On the Earth**,* exposure of persons to ionizing radiation shall be controlled as specified in [24], the procedures should be based on the principle of justifying the need for, optimizing, and limiting exposure to ionizing radiation.

- No practice which exposes persons to radiation may be adopted unless its introduction is essential and the result cannot be achieved by other methods which avoid such exposure.
- No practice which exposes persons to radiation may be adopted until it has been ensured that such exposure is kept to the minimum reasonably achievable on the reasonably achievable minimum, social and economic factors are taken into account (the ALARA principle).

Dose record keeping is usually needed only for category A of persons, e.g. with possible exceeding of annual ***E*** 6 mSv.

Exposure to ionizing radiation may be reduced by applying one or more very simple rules: reduce the intensity of the radiation source used; increase the distance between the exposed person and the source; reduce the time of exposure to ionizing radiation; reduce radiation levels by the use of suitable shielding.

None of these reduction possibilities is directly and simply applicable for onboard space- and aircraft exposure. For these exposures, only reduction through flight type and time is possible, the approaches, how this reduction could be done, differ for space and air-flights.

As far as the ***onboard aircraft exposure*** is concerned, the legal consequences of the ICRP recommendation were considered by the European Council in its Basic Safety Standards (Directive 96/29/Euratom) [25]. The protection of air crew (Article 42) is therein formulated as

Each Member State shall make arrangements for undertakings operating aircraft to take account of exposure to cosmic radiation of air crew who are liable to be subject to exposure to more than 1 mSv per year. The undertakings shall take appropriate measures, in particular:

- *to assess the exposure of the crew concerned,*
- *to take into account the assessed exposure when organizing working schedules with a view to reducing the doses of highly exposed aircrew,*
- *to inform the workers concerned of the health risks their work involves, and*
- *to apply Article 10 to female air crew, e.g. that the equivalent dose to the child to be born will be as low as reasonably achievable and that it will be unlikely that this dose will exceed 1 mSv during at least the remainder of the pregnancy*

Technical guidance on ways to include in regulations “a significant increase in exposure due to natural radiation sources” was issued by the Commission in 1997 [26]. A special section is concerned with the protection of aircraft crew, it is covered by three following paragraphs:

- *For air crew whose annual dose falls in the range 1-6 mSv there should be individual estimates of the dose. These estimates of dose should be made available to the individual concerned. For flights below 15 km these may be carried out using an appropriate computer program and internationally agreed information,*
- *It will normally be possible to adjust rostering so that no individual exceeds 6 mSv per year. However, for air crew whose dose is likely to exceed 6 mSv, record keeping in the sense of the Directive is recommended with appropriate medical surveillance.*
- *It would be unnecessary and unhelpful to declare supervised or controlled areas in aircraft.*

Civil aviation is an international business and it is essential that it is regulated in a similar way in different countries. The civil aviation authorities co-operate through an organisation called the Joint Aviation Authorities (JAA). The European radiation protection Basic Safety Standards Directive is considered in JAR-OPS 1.390.

Particular practise of radiation protection of aircraft crew members differs in particular countries, overall situation is not completely known. For example, in some countries the dose record keeping is obligatory for all aircraft crew members.

As far as the ***space- and onboard aircraft exposure*** is concerned it is recommended [2]:

- *Dose assessment for astronauts should take profit the combination of radiation transport calculation and measurements; the main features of the approach should include sequential assessment of the radiation environment at the exterior as well as in the interior of spacecraft, EVA cases included. The combination of measurements and calculation should provide an estimate of the dose quantities within a factor 1.5 (2s);*
- *Operational radiation monitoring consisting of area monitors and personal dosimeters should ensure the use for both dose assessment as record keeping purposes;*
- *Implementation of immediate dose management actions should be ensured;*

- *Astronauts should receive an annual confidential report on their radiation dose assessment*

Main objectives of operational safety program should be:
1. to facilitate actions, both in advance of a mission and in flight with the goal to influence significantly the levels of radiation exposure;
2. to collect and record astronauts doses for individual missions and cumulative career record; and
3. to identify, plan and inform practical ALARA actions to avoid unnecessary levels of radiation exposure

4. Methods of exposure level estimation

4.1. Experimental methods

The dosimetry in space, onboard space- and/or aircraft radiation fields represents a complex task, with large diversity of the particle types, theirs energies and the ranges of LET. When compared to lower energy radiation, their penetration capabilities are high, the importance of nuclear interactions to particle's transport and to the energy transfer could be much more important. Besides, many methods used for lower energy radiation specifically for one type of radiation fail, because they start to be sensitive to other radiation types present in the fields as well.

The choice depends also on the high energy radiation field: in space predominate high energy charged particles, last studies has drawn attention also to the neutron component onboard spacecraft [18]; onboard aircraft neutrons predominate in the high LET component, the electrons and high-energy protons contribute the most in low LET component.

In spite of these differences, many methods are universally used. Generally, two basic approaches to determine dosimetric characteristics exist:
1. The direct, straightforward, method is to measure the total dose due to all components of a field together and, when dose equivalent is needed, also the quality factor. The detailed composition of the radiation field needs not to be known in this case.
2. The second method is based on the separate determination of doses (or fluences) for each major component of the field. When the fluence is measured, the energy spectrum for a component should be known.

The dosimetry methods and detectors frequently used in high energy radiation fields are shown in Table 6. They are divided following the delivery of information (active - on line data available) and also the component to be characterized. The extent of this contribution does not permit to discuss these methods in detail. More complete information can be found, for example, in [5,6,10-13,19,20].

There are several possible choices to characterize *low LET component.* The TLDs are the most popular low LET dosimeter for these purposes. It has however to be mentioned that they are as well as other devices relatively much more sensitive to other components (neutrons!) when compared to low energy fields. As far as other detectors are concerned, Si-diode or GM counter based electronic personal dosemeters (EPD) have been also tested for such purposes.

To characterise *total radiation field characteristic,* microdosimetric tissue equivalent proportional counters (TEPC) are proposed to be used as reference instruments [10-12]. The main advantage of this equipment is that it measures directly the distributions of energy transfer events in the microdosimetry quantity lineal energy (related to LET) independently of the particle at the origin of such event, i.e. it belongs to the first type of methods mentioned. The corresponding total dose or dose equivalent can be therefore directly calculated through the equations:

$$D = \int (dN/dL) * L * dL \text{ ; resp.} \tag{1}$$

$$H = \int (dN/dL) * L * Q(L) * dL \text{ ;} \tag{2}$$

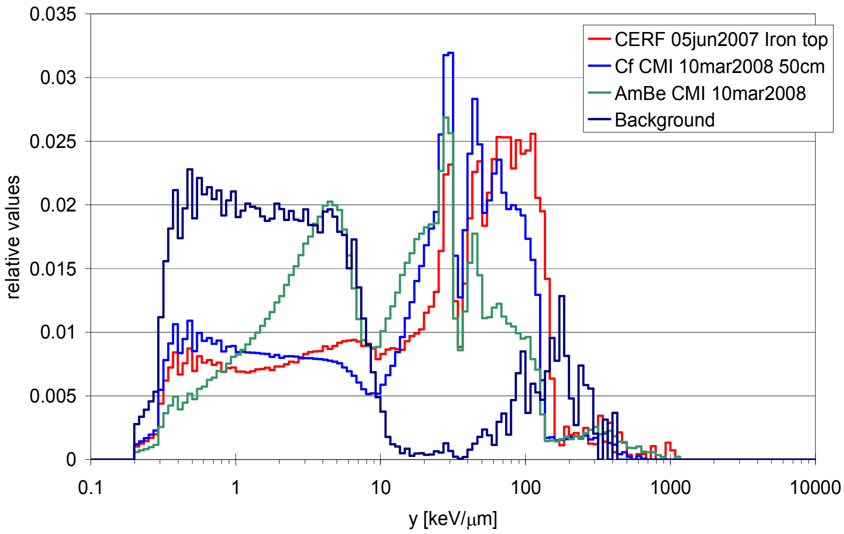
where dN/dL is the number of events in a LET interval;; L is value of LET; and Q(L) is the quality factor corresponding to the value of L.

Microdosimetry spectra measured by means a TEPC in different fields are shown in Fig. 8.

Table 6: Basic dosimetry methods and detectors tested for use in space and flight radiation fields

Component	Type	Dosimetry method, detector
low LET	active	ionization chambers, GM-counters, Si-diodes, scintillation counters
(electron, mesons, photons)	passive	luminescent detectors (TLD, OSL), photographic films
high LET	active	moderator - type devices, recoil proton spectrometers
(neutrons)	passive	track etched detectors (TED), bubble detectors, activation detectors, nuclear emulsions,
all LET	active	microdosimetric TEPC; ionization chambers, special semiconductor devices or GM-counters

Figure 8: Microdosimetry spectra measured by means of HAWK TEPC [21].



One of the most important aspects of space- and aircraft onboard measurements is *the calibration of instruments*. There are no available reference fields for all components of the radiation to be measured [11,13,20,23].

Usually, photons of ^{60}Co are used for calibration of instruments intended to characterise low LET component in these radiation fields.

As far as high LET (neutron) component is concerned, the CERF high-energy reference neutron facility at CERN [22] has been widely used for calibrations and comparisons of instruments. In many cases neutron detectors were calibrated also with common radioisotope sources (AmBe, Cf, PuBe). Track etch detectors derive a high-LET ambient dose equivalent component from an independent method of calibration, based on the irradiation in heavy ion beams [9,11,13].

4.2. Transport codes available

There are a number of radiation transport codes used to calculate the radiation field at aircraft altitudes and at sea level produced by galactic cosmic radiation. There are similar number of methods in current use, which are based on these codes to compute dose to aircraft crew, for example CARI (using LUIN), EPCARD (using FLUKA), FREE (using PLOTINUS related to LUIN), PC-AIRE (using

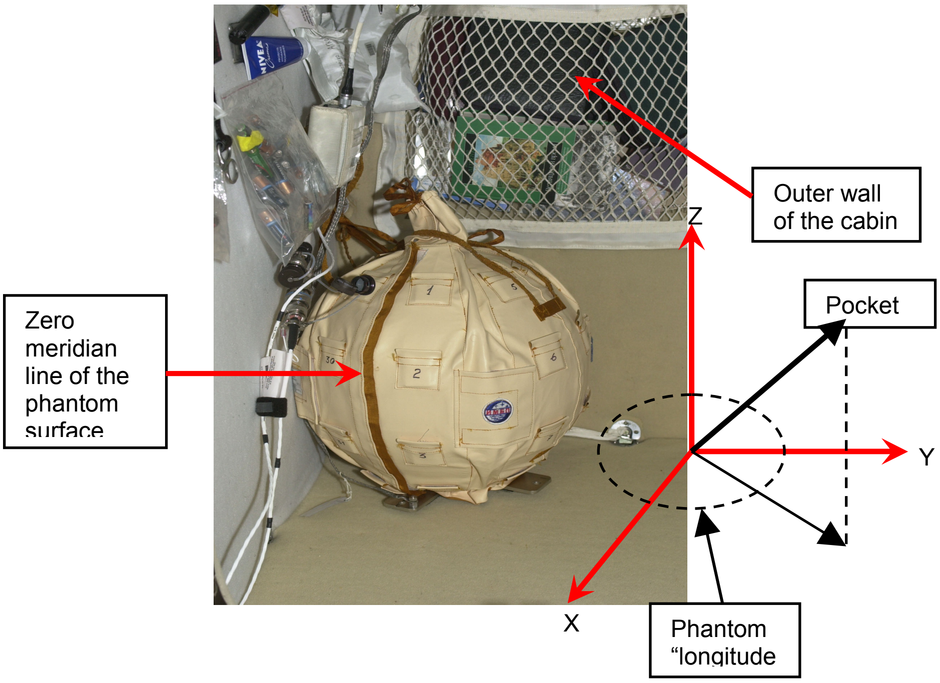
experimental measurements with fitting), SIEVERT (using the data from CARI, and since January 2004 from EPCARD), and the algorithm of Pelliccioni (using FLUKA). None of those consider the influence of the aircraft on the particle fluence. They are described in more details in [11].

4.3. Results of some onboard space- and air-craft measurements

As an example of ***onboard spacecraft measurements,*** the results obtained during a MATRJOSHKA-R experiment onboard ISS can be presented [9]. Passive detectors have been used in this experiment, PADC TED LET spectrometers, and Al_2O_3:C and $CaSO_4$:Dy TLDs. Detectors have been transported to ISS on 21/12/2005; and returned to Earth on 20/09/2006 (total exposure time – 273days). Onboard of ISS they were exposed on the surface and in the Matroshka – R phantom (see Fig. 9) in following way:

- in two containers inserted into the spherical phantom up to the depth 10 cm;
- in 8 pockets (Nos. 2, 8, 10, 16, 18, 24, 26, and 32) on the surface of the phantom.

Figure 9: Flight unit of the phantom in the working jacket installed in the ISS crew cabin



Main results obtained during the experiment Matrjoshka-R 2006 can be summarize as follows:

1. No important differences are observed in LET spectra neither in pockets, nor in containers.
2. There is a good correlation of TLDs and PADC track etch LET spectrometer's data,
3. One observes a slight (~30%) decrease of dosimetric characteristics at the depth of 10 cm in the phantom.
4. When combining TLD and LET spectrometers data, the daily values of dosimetric characteristics can be obtained, they are presented in Table 7, one see that both *D* and *H* vary by a factor up to 2.

Table 7: Daily values of dosimetric and microdosimetric characteristics as measured with TLDs and TED LET spectrometers onboard of ISS on and inside the Matrjoshka phantom (12/05-09/06)

Quantity, unit	Container 3	Container 13	Pockets
D, µGy	127 - 149	145 - 196	142 - 241
H, µSv	296 - 346	307 - 431	328 - 520
QF	2.3.-.2.5	2.0 – 2.5	2.0 – 2.5

Several intercomparisons of ***onboard aircraft dosimetry methods*** have been realised. As an exemple, the results of onboard aircraft intercomparison during a long haul flight are presented in Table 8, the results of our own measurements onboard Czech Airlines aircraft during 3 years of long term monitoring runs in the Table 9.

Table 8: Comparison of different measuring methods onboard an aircraft during the round trip Paris-Fairbanks-Tokyo-Fairbanks-Paris [13], in μSv

Method	Non-neutron component	Neutron component	Total
TEPC's	49	69	118
Si-detector	58	84	142
GM counter	78		
EPD's	65		
TLD's & TED's	51	77	124
Bubble detectors		67	
Average	54 ± 5	76 ± 9	129 ± 10

Table 9: Comparison of integral data (in mSv) measured and calculated for long term monitoring runs 2005–2007 onboard a CSA aircraft

Method	Quantity	Year / Flight time [hours]		
		2005 / 2754	2006 / 3127	2007 / 3882
CARI6	E_{total}	11.9	15.6	18.9
EPCARD3.2	E_{total}	11.7	12.8	18.6
EPCARD3.2	H*(10), total	10.0	10.6	15.6
MDU	H(E)app., (total)	11.0 ± 1.6	14.0 ± 2.1	*)
EPCARD3.2	H_{low}	4.3	4.9	5.7
MDU		5.0 ± 0.6	5.2 ± 0.6	*)
$CaSO_4$:Dy		–	5.2 ± 0.5	5.7 ± 0.6
AlP glass		4.4 ± 0.4	5.4 ± 0.5	5.6 ± 0.6
Al_2O_3:C		4.2 ± 0.4	5.9 ± 0.6	6.3 ± 0.6
EPCARD3.2	H_{high}	5.7	6.1	9.8
MDU		6.2 ± 0.9	8.0 ± 1.2	*)
LETspect.- Page		3.6 ± 0.6	3.6 ± 0.6	5.2 ± 0.7
LETspect.Tastrak		4.4 ± 0.7	3.1 ± 0.5	5.4 ± 0.9

*) evaluation not yet finished

4.4. Aircraft crew individual monitoring

The individual aircraft crew monitoring by means of experimental measurements is judged as not entirely satisfactory. Usually used passive individual dosimeters (TLD, TED, albedo) are not sensitive enough, theirs energy dependencies are not optimal. Electronic individual dosimeters are expensive, their characteristics are not satisfactory for neutron component. That's the reason why, since the beginning of 90's, it was generally agreed that the calculation would be preferred as the method of aircraft crew individual monitoring [10-12,25]. Several calculation codes were developed and are used (see sub-chapter 4.2.) for that purpose. As an example of such monitoring, the results obtained since 1998 in Czech Republic are presented. Up to now the code CARI developed in the USA [14] has been used. Overview of results obtained is presented in Figs. 10 and 11 [21].

One can see that:

1. Average annual effective dose anticorrelates, as expected, due to globally similar route flights schemes with solar activity; its average value varying between 1.6 and little more than 2 mSv;
2. Collective dose regularly increases, mostly due to the increase of aircraft crew numbers.

3. At 2007 this dose reached close to 25 % of total occupational collective dose in Czech Republic.

It should be, however, added that CSA is rather small company, with relatively low contribution of long-haul flights. For bigger companies, individual annual effective doses could exceed 6 mSv. The level of exposure regularly increases, for example several CSA aircraft crew members exceeded in 2007 annual value of 4 mSv.

Figure 10: Global results of aircraft crew individual monitoring in Czech Republic - 1

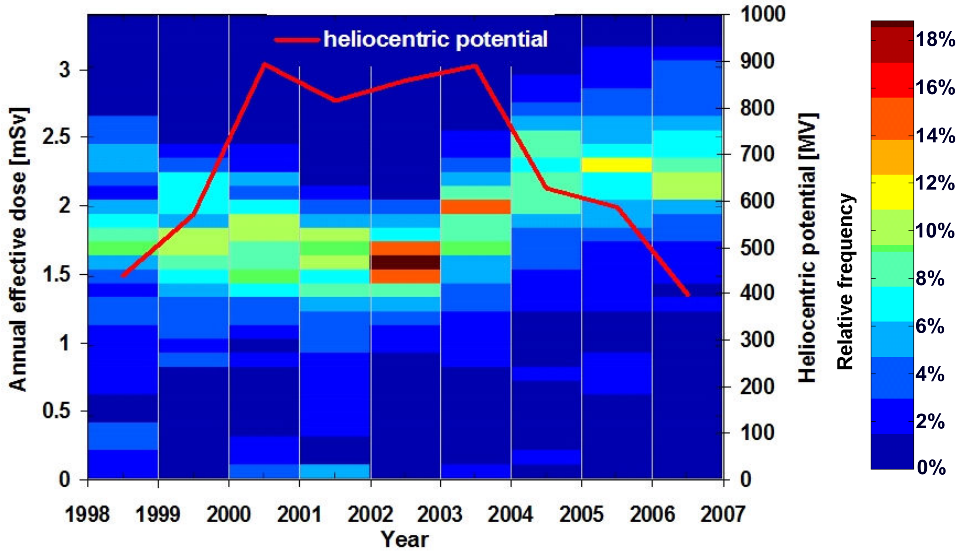
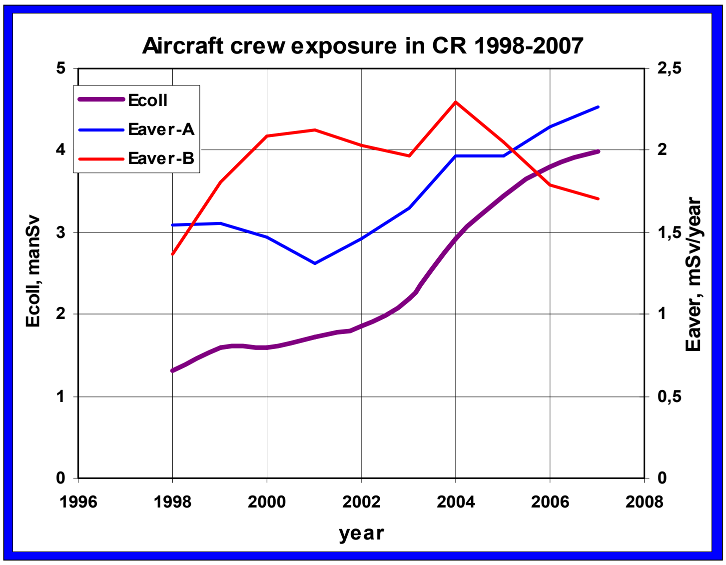


Figure 11: Global results of aircraft crew individual monitoring in Czech Republic – 2



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